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TSUNAMI HAZARD MAPPING OF ALASKA COASTAL COMMUNITIES

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INTRODUCTION

Alaska has the greatest earthquake and **tsunami** potential in the entire United States. The communities of south-coastal Alaska occupy one the most seismically active regions of the world, where the Pacific Plate is subducting under the North American Plate. This subduction zone, the Alaska–Aleutian megathrust zone, creates high tsunami hazards for the adjacent coastal areas. The **coseismic** crustal movements that characterize this area have the potential for producing vertical sea-floor displacements, which are highly **tsunamigenic**. Historic tsunamis that were generated by earthquakes in the Alaska–Aleutian subduction zone have resulted in widespread damage and loss of life along the Alaskan Pacific coast and other exposed locations around the Pacific Ocean. Large seismic events occurring in the vicinity of the Alaska Peninsula, Aleutian Islands, and Gulf of Alaska have a very high potential for generating both local and Pacific-wide tsunamis. Seismic water waves originating in Alaska can travel across the Pacific and destroy coastal towns hours after they are generated. However, they are considered to be a near-field hazard for Alaska, and can reach Alaskan coastal communities within minutes after the earthquake. Therefore, saving lives and property depends on how well a community is prepared, which makes it essential to estimate the potential flooding area of the coastal zones in a case of a local or distant tsunami.

To help mitigate the risk these earthquakes and tsunamis pose to Alaskan coastal communities, the Geophysical Institute (GI) of the University of Alaska Fairbanks and the Alaska Division of Geological & Geophysical Surveys (DGGS) participate in the National Tsunami Hazard Mitigation Program (NTHMP) by evaluating and mapping potential inundation of selected parts of Alaska coastlines using **numerical modeling** of tsunami wave dynamics. The communities for inundation modeling are selected in coordination with the Alaska Division of Emergency Services (ADES) with consideration to location, infrastructure, availability of bathymetric and topographic data, and willingness for a community to incorporate the results in a comprehensive mitigation plan (table 1).

The production of tsunami evacuation maps consists of several stages. First, we construct hypothetical tsunami scenarios on the basis of the parameters of potential underwater earthquakes. Then we perform model simulations for each of the

Table 1. *Prioritization of Alaska coastal communities for tsunami-inundation mapping. Population is based on 1990 census. Italics indicate communities scheduled for mapping, and current order. Bathymetry codes: 1=good, 2=fair, 3=poor (*new bathymetric data are currently being acquired for Sitka and Seward). Homer and Seldovia will be mapped simultaneously.*

Coastal community	**High Potential for Distant Tsunamis**	**Strong Community Involvement**	**Bathymetry**	**Population**	**Infrastructure**	**Tourism**	**Cruise Ships (Tour Bus/Ship)**	**Special Seasonal Events**	**Commercial Fishing / Timber**	**Large Scale USGS Base Maps**
Adak	✓		1-2	7	✓				✓	
Akutan			1	408				✓	✓	
Cold Bay			2	103	✓			✓	✓	
Cordova (9)		✓	3	2,571	✓	✓	✓	✓	✓	✓
Craig			3	2,145	✓	✓		✓	✓	✓
Elfin Cove			2	50		✓			✓	
Haines			3	1,463	✓	✓	✓	✓	✓	✓
Homer (2)	✓	✓	1	4,155	✓	✓	✓	✓	✓	✓
Juneau/Douglas			3	30,684	✓	✓	✓	✓	✓	✓
Ketchikan		✓	2	8,460	✓	✓	✓	✓	✓	✓
King Cove	✓		2	1,947	✓			✓	✓	
Kodiak (1)	✓	✓	1	8,864	✓	✓	✓	✓	✓	✓
Nikolski	✓		?	35						
Ouzinkie	✓		2	252	✓	✓		✓	✓	
Perryville	✓		2	107				✓	✓	
Petersburg			3	3,398	✓	✓		✓	✓	
Port Lions			2	242	✓	✓		✓	✓	
Sand Point (5)	✓	✓	2	830	✓			✓	✓	
Seldovia (2)	✓	✓	1	281	✓	✓	✓	✓	✓	✓
Seward (3)	✓	✓	3*	3,090	✓	✓	✓	✓	✓	✓
Shemya	✓		1	0						
Sitka (4)	✓	✓	2*	8,779	✓	✓	✓	✓	✓	✓
Skagway			3	814	✓	✓	✓	✓		✓
Unalaska (6)	✓	✓	1	4,285	✓	✓	✓	✓	✓	
Valdez			2	4,155	✓	✓	✓	✓	✓	✓
Whittier (8)		✓	1	306	✓	✓	✓	✓	✓	✓
Wrangell			2	2,589		✓	✓		✓	
Yakutat (7)	✓		1	810	✓	✓		✓	✓	✓

***Bolded words are defined in glossary.**

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earthquake source scenarios. The results are compared with any observations from historical tsunamis in the region, if such data exist. Finally, numerical results and historical observations are combined to develop a worst case scenario for a tectonically generated tsunami for every community on a map. The inundation line produced by this scenario becomes a basis for local tsunami hazard planning and construction of evacuation maps.

TSUNAMI HAZARD MAPPING OF KODIAK AND VICINITY

The Kodiak area was identified as a high-priority region for Alaska inundation mapping. Kodiak's vulnerability to tsunamis was demonstrated by the 27 March 1964 earthquake (**moment magnitude** 9.2). In the city of Kodiak, the tsunami caused six fatalities and about $30 million in damage. Since then, the harbor and waterfront area of the city that was destroyed by the 1964 tsunami has been rebuilt and significantly expanded, and substantial additional growth of the city of Kodiak and other nearby communities has occurred. The preferred sites for runup modeling were determined by ADES and Kodiak local government officials to be the three communities of metropolitan Kodiak: the city of Kodiak, U.S. Coast Guard Reservation (USCGR) and Womens Bay (fig. 1). Local and state emergency managers have requested maps showing the extent of inundation with respect to human and cultural features as a basis for preparing evacuation maps for these communities.

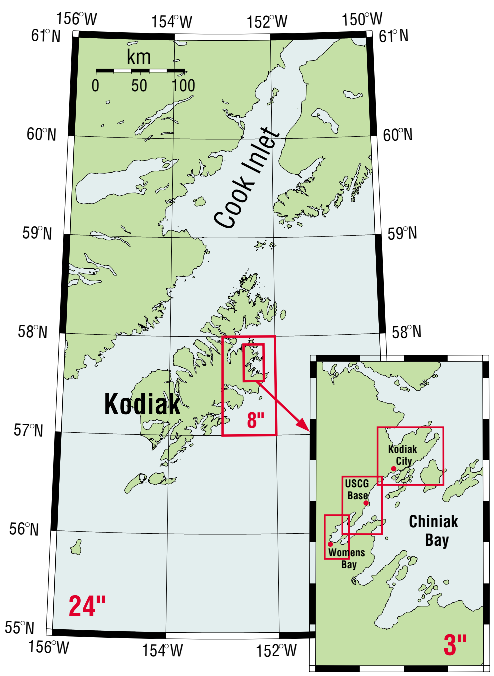

Figure 1. *Large rectangle encompasses Kodiak Island grid area of 24-arc-second resolution. The two small rectangles delineate the 8-second and the 3-second grids. Inset figure shows the 3-second grid, which includes 1-second grids for the Kodiak Island communities of Kodiak city, USCGR, and Womens Bay, where runup calculations were performed.*

Tsunami hazard maps that we recently prepared for the Kodiak area (Report of Investigations 2002-1) represent the first step in the State of Alaska tsunami hazard evaluation and production of inundation maps for many Alaskan coastal communities. Two 1:12,500-scale maps show inundation lines calculated for seven different tsunami scenarios, one map for the city of Kodiak and the other for USCGR and Womens Bay. A sample of the inundation map for the city of Kodiak appears in figure 2. Two corresponding maps show the estimated extent of inundation in the same communities resulting from the "worst case scenario," which is the maximum inundation of all modeled scenarios as well as areas of observed 1964 tsunami effects that extended farther inland than all of the modeled inundations.

We calculated the extent of inundation caused by tsunami waves using numerical modeling of tsunami wave runup. We ran the models at the Arctic Region Supercomputing Center at the University of Alaska Fairbanks. To propagate the wave from a source to various coastal locations we used four embedded bathymetric and topographic data grids, increasing in resolution from 2 arc minutes (2 km x 3.7 km at 55°N latitude) in the Gulf of Alaska to 1 arc second (21.8m x 27.5m at 57°47' latitude) in the three grids that cover communities selected for inundation modeling. Areas covered by the embedded grids are shown in figure 1.

We conducted all model runs using bathymetric data that correspond to Mean Higher High Water (MHHW). For the generation mechanism, we modeled only earthquakes as potential sources of tsunami waves. In 1964, there were about 20 local submarine and subaerial landslide-generated waves that

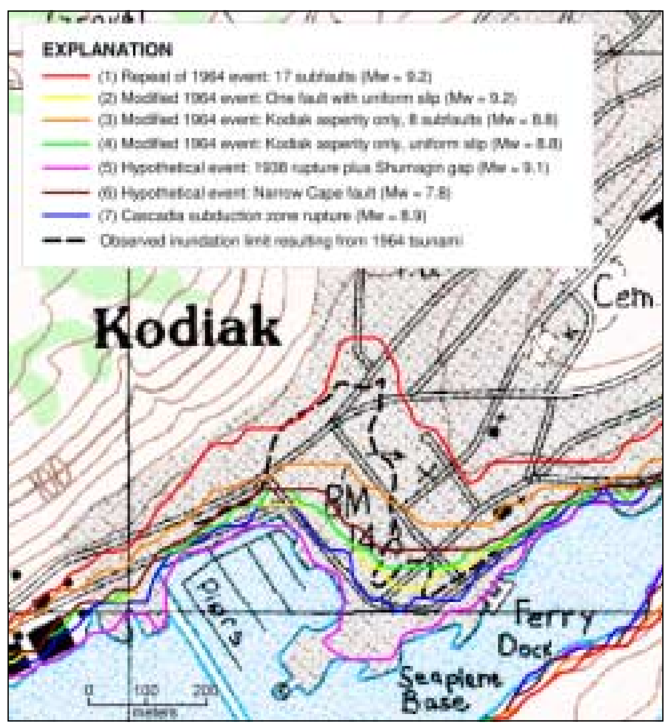

Figure 2. *Sample of tsunami-inundation map for the area of downtown Kodiak. Base is from U.S. Geological Survey topographic map of Kodiak D-2 SE Quadrangle.*

were limited to the bays of generation and caused substantial damage. Because inundation in the Kodiak area in 1964 was caused primarily by **tectonically generated tsunamis**, landslide wave sources were not considered within the scope of this generation model.

MODELING OF THE 1964 TSUNAMI

We initiated this project with the modeling of the Alaska 1964 tsunami, because this event is probably the worst-case scenario of a tsunami for the Kodiak Island communities and is useful for testing the results of our modeling on the basis of a well documented historical event. The 1964 Prince William Sound earthquake generated one of the most destructive tsunamis observed in Alaska and the west coast of the U.S. and Canada. This major tectonic tsunami was generated in the trench and upper plate fold and thrust belt area of the subduction zone (Plafker and others, 2000) and affected all the communities in Kodiak and the nearby islands. On Kodiak Island the 1964 tsunami was studied in depth by several investigators (for example, Kachadoorian and Plafker, 1967; Wilson and Torum, 1968), and their observed inundation patterns are available for calibration of the model. Christensen and Beck (1994) demonstrated that there were two areas of high **moment** release, representing the two major **asperities** of the 1964 rupture zone: the Prince William Sound asperity and the Kodiak Island asperity. A detailed analysis of the 1964 rupture zone was presented by Johnson and others (1996), who derived a slip distribution for the 1964 earthquake as shown in figure 3.

To construct a source function for the 1964 event, we used the fault dislocation model developed by Johnson and others (1996), with eight subfaults representing the Kodiak asperity, and nine subfaults in the Prince William Sound asperity. We used the equations of Okada (1985) to calculate the distribution of coseismic uplift and subsidence resulting from the given slip distribution. Then, the derived surface deformation was used as the initial condition for tsunami propagation. During a model run, the initial topography was modified to account for residual seismic deformation of land due to the earthquake.

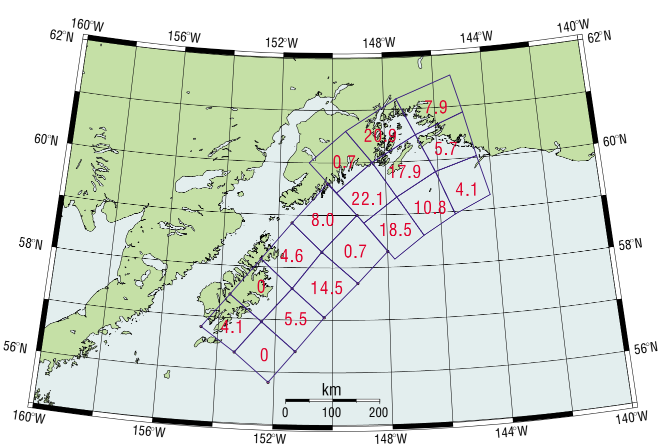

Figure 3. *Slip distribution of the 1964 earthquake, from Johnson and others (1996). Numbers represent slip in meters on each subfault.*

We modeled the 1964 tsunami wave using two different source functions for comparison. The first one, described above, consists of 17 subfaults, each having its own parameters. The second source function represents a simple single fault with uniform slip distribution (scenario 2). The amount of slip on the single fault was calculated in a way that preserves the seismic moment corresponding to the moment magnitude of 9.2. For both scenarios, the model propagates the initial displacements from the source to coastal locations through the set of embedded grids of increasing resolution.

In figure 2, the broken black line delineates the area inundated in 1964 on the basis of data collected after the event. The solid red line shows the inundation limit computed using the complex source function of 17 subfaults (scenario 1). The yellow line is the computed inundation limit that corresponds to the simple one-fault source model for the 1964 event (scenario 2). The results show that the wave generated by the complex source model with detailed slip distribution produces inundation close to that observed in 1964. Similar results were obtained for the USCGR area. The one-fault model greatly underestimates the extent of flooding caused by the 1964 tsunami wave.

OTHER HYPOTHETICAL TSUNAMI SCENARIOS

We considered several additional hypothetical earthquake scenarios as potential sources of tsunami waves that can affect the Kodiak area. These scenarios represent both distant and local sources, and we modeled several using a simple one-fault source function as well as the multiple fault approach. The published maps show seven different tsunami inundation limits that correspond to these scenarios, including those described above for the 1964 event:

Scenario 1. Repeat of 1964 event: 17 subfaults. This source model is described in detail in the above section.

Scenario 2. Modified 1964 event: One fault with uniform slip. This source model provides a comparison with scenario 1 to show the importance of the detailed slip distribution of the rupture zone for the near-field inundation modeling and hazard assessment. To accomplish that, we constructed another source function for the 1964 event, consisting of a single fault with uniform slip distribution. The amount of slip on the single fault was calculated in a way that preserves the seismic moment.

Scenario 3. Modified 1964 event: Kodiak asperity only, eight subfaults. This source function represents the southern asperity of the 1964 rupture zone. According to Christensen and Beck (1994), the two segments of this zone behaved independently in the past, with the Kodiak Island region rupturing more frequently. That allowed us to consider the Kodiak asperity of the 1964 rupture as an independent source with a potential of generating tsunami waves. We modeled this source using the eight most southwestern subfaults of the 1964 fault mosaic as shown in figure 3.

Scenario 4. Modified 1964 event: Kodiak asperity only, uniform slip. This scenario describes the same hypothetical event as scenario 3, but with uniform slip distribution within the rupture area. Scenarios 3 and 4 have the same seismic moment.

Scenario 5. Hypothetical event: 1938 rupture plus Shumagin gap. To create a hypothetical event in the Alaska–Aleutian megathrust zone, we combined the rupture area of the 1938 earthquake with the Shumagin gap area, assuming that the rupture can propagate southwestward into the 1946 rupture zone. This scenario produces the least inundation of all scenarios (purple line in figure 2) because of the oblique incidence angle of wave arrival from the southwest.

Scenario 6. Hypothetical event: Narrow Cape fault. The Narrow Cape fault is part of a series of northeast-trending thrust faults that extend across southeastern Kodiak Island and into the northwestern Gulf of Alaska (fig. 4). The geomorphic expression of this fault at Narrow Cape suggests that its most recent displacement occurred during Holocene time, making it worthy of consideration as a potential source for a local tsunami. We selected the 1999 ChiChi earthquake in Taiwan as a hypothetical analog for displacement on Narrow Cape fault, because the Chenlungpu fault on which that earthquake occurred is in a very similar tectonic setting. Our model uses three steeply dipping subfaults of approximately equal length, with slips of 9.6 m, 4.9 m, and 3 m from southwest to northeast, respectively, to generate an earthquake of moment magnitude 7.8.

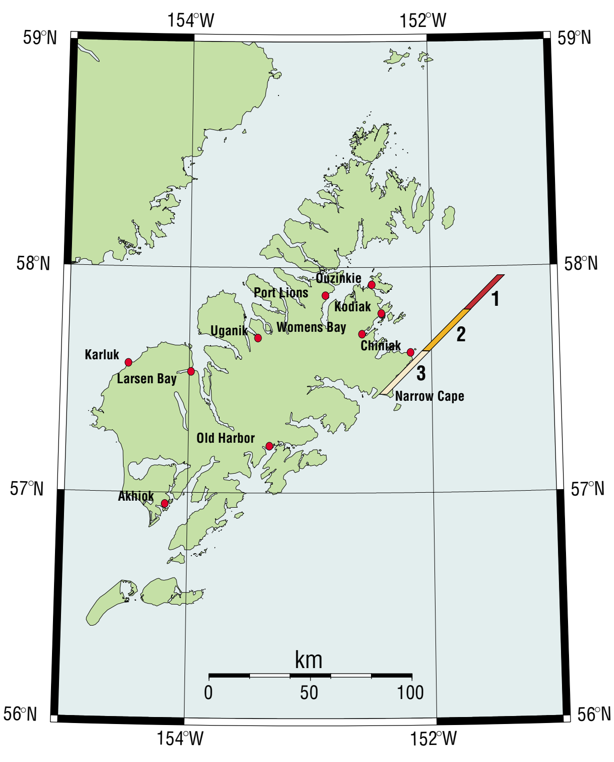

Figure 4. *Map of Kodiak Island showing hypothetical rupture zone of Narrow Cape fault divided into three subfaults. Displacement is upward on the northwest side, 3 m on section 1, 4.9 m on section 2, and 9.6 m on section 3.*

Scenario 7. Cascadia subduction zone rupture. This scenario represents one of the distant tsunami sources that can affect the Kodiak Island communities. The source function is based on the occurrence of a moment magnitude 8.9 subduction earthquake off the coast of Washington and Oregon.

TSUNAMI-INUNDATION MAPS FOR THE KODIAK AREA

The results of our model calculations for the Kodiak vicinity appear on the published maps as inundation-limit lines for each of the seven tsunami scenarios. Separate map sheets show a single line representing the maximum inundation from all scenarios for use by emergency managers. With the exception of part of Womens Bay, the worst-case tsunami scenario for the three Kodiak communities is the inundation caused by the modeled 1964 event with 17 subfaults. The Narrow Cape fault source produced the second largest inundation zone after the inundation caused by the 17-fault model of the 1964 earthquake in almost all locations, and exceeded the modeled 1964 inundation in part of Womens Bay. This result implies that a local offshore earthquake of smaller magnitude can generate a wave comparable to that produced by a great megathrust earthquake.

In addition to the published 1964 inundation limits in downtown Kodiak and USCGR (Kachadoorian and Plafker, 1967), we obtained local observations to help estimate the actual inundation at other locations in our project area. These included observations by local residents who were present at the time of the 1964 event and the inland extent of driftwood and tsunami-deposited sand in the vicinity of Womens Bay. These observations identified a few areas where the actual inundation in 1964 extended farther inland than the inundation from any of our modeled scenarios, most notably in the vicinity of Womens Bay. The maximum inundation lines shown on the published maps include these areas of locally documented effects of the 1964 tsunami. We also made some manual adjustments to the final maximum inundation lines on the basis of detailed local topography in the area of downtown Kodiak where the topography is not accurately resolved by the available digital elevation model.

INUNDATION MAPPING FOR OTHER COASTAL COMMUNITIES

We are in the process of acquiring available bathymetric and topographic data for the Homer and Seldovia areas and have begun wave-model calculations there using the 17-subfault model for the 1964 earthquake. A new bathymetric survey has recently been completed in the Seward area, and another is currently underway in the Sitka area. Our goal is to complete tsunami-inundation maps for Homer–Seldovia and the next three priority areas, Seward, Sitka, and Sand Point, over the next two years. Thereafter, we will develop inundation maps for the four remaining communities in order of the priorities indicated in table 1. Other communities will be considered for future mapping pending program funding.

Tsunami-inundation maps are useful for state and local emergency managers to identify areas that should be evacuated in the event of a major tsunamigenic earthquake, and to delineate evacuation routes. Because of the uncertainties inherent in this type of modeling, these results are not intended for land-use regulation.

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GLOSSARY

asperity – an area of a fault where more strain accumulates than in other areas; consequently, during earthquakes, the largest displacements tend to occur on asperities

coseismic – occurring simultaneously with an earthquake

moment magnitude – a measure of the size of an earthquake, calculated on the basis of seismic moment and reported as a value on the Richter scale

numerical modeling – mathematical simulation of a natural process, often with the use of a powerful computer

seismic moment – the rigidity of the rock times the area of faulting times the amount of slip

tectonically generated tsunami – a tsunami generated by vertical motion of the seafloor rather than by a landslide, volcanic eruption, or meteorite impact

tsunami – A sea wave produced by a disturbance of the ocean floor, usually by a shallow submarine earthquake, but also by submarine earth movement, subsidence, or volcanic eruption. These seismic sea waves can travel up to 950 km/hr, and can pile up to heights of 30 m or more when they enter shallow water along an exposed coast

tsunamigenic – capable of generating a tsunami

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Historically DGGS has generated and compiled new geologic data but has not emphasized geologic modeling of that data. The advances in computing power, in both desktop systems and accessibility to supercomputers, combined with evolving software, are beginning to add a new dimension to DGGS work.

Through interagency collaborations and the in-house training of our geologic staff, new geologic modeling tools are being integrated with DGGS projects. In addition to Engineering Geology Section Chief Rod Combellick's work in modeling earthquake-related phenomena in the Kodiak, Anchorage, and other coastal Alaska areas, we have a senior engineering geologist being trained at the graduate level in remote sensing technologies, our Energy Resource Assessment Section is learning to model seismic data, and our Mineral Resource Appraisal section is developing a suite of Geographic Information System (GIS) applications to enhance DGGS's regional mapping capabilities.

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